

Muon Anomalous Magnetic Moment $(g - 2)_\mu$ and the Randall-Sundrum Model

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Abstract

We study the effects of the Kaluza-Klein gravitons in the Randall-Sundrum model on the recent BNL measurements of the muon $(g - 2)$ deviation from the standard model prediction. By examining the J -partial wave unitarity bounds of the elastic process $\gamma\gamma \rightarrow \gamma\gamma$, the cut-off on the number of massive KK gravitons, n_c , has been introduced. We found that the recently measured Δa_μ can be accommodated in the RS model, within the natural parameter space allowed by the perturbative unitarity. For example, dozens (hundreds) of the n_c for $\Lambda_\pi = 1 \sim 2$ TeV (3 TeV) can explain the reported Δa_μ .

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1. Introduction. As one of the most accurately measured quantities in particle physics, the anomalous magnetic moment of the muon, $(g - 2)_\mu$, has played an important role in providing constraints on various models for physics beyond the standard model (SM). The recent Brookhaven E821 results for the $a_\mu \equiv (g - 2)_\mu/2$ by a 2.6 standard-deviation from its SM prediction [1],

$$\Delta a_\mu = a_\mu(\text{exp}) - a_\mu(\text{SM}) = (43 \pm 16) \times 10^{-10}, \quad (1)$$

therefore, is very likely to indicate that the SM should be extended just above the electroweak scale. A conservative view still exists such that the uncertainties in the SM calculations of the hadronic vacuum polarization may explain the deviation [2]. The implications of the Δa_μ on new physics have been extensively studied. Supersymmetric models are shown to accommodate this Δa_μ , as being consistent with all other relevant constraints [3]. Interesting results are that the reported Δa_μ value favors large $\tan \beta$ case and imposes observable upper bounds on the masses of supersymmetric particles. The effects from other new physics such as technicolor models [4], lepton flavor violation [5], composite models [6], leptoquark models [7], and others [8] have been also studied.

Based on a theoretical motivation to explain the gauge hierarchy problem, a novel approach has been proposed by introducing extra dimensions: Arkani-Hamed, Dimopoulos and Dvali (ADD) proposed that the large volume of the extra dimensions with factorizable geometry can explain the observed largeness of Planck scale M_{Pl} , whereas the fundamental string scale M_S being maintained around TeV scale [9]; based on two branes and a single extra dimension with non-factorizable geometry, Randall and Sundrum (RS) have proposed another high dimensional scenario, where the gauge hierarchy is attributed to a geometrical exponential factor [10]. The phenomenologies of both extra-dimensional models have been extensively studied [11]. In this paper, we examine if the RS model can explain the observed Δa_μ deviation.

In the four-dimensional effective theory, both extra dimensional scenarios yield the Kaluza-Klein (KK) states of massive gravitons. The KK gravitons in the ADD case have

almost continuous spectrum up to a cut-off scale M_S with the Planck suppressed interaction; those in the RS case show discrete mass spectrum about TeV scale with the electroweak scale (Λ_π) interactions. In the ADD case, the calculation of the KK graviton contribution to the muon ($g-2$) has shown some interesting results such that a given KK graviton generates finite contribution to the Δa_μ [12]; the universal coupling of each KK graviton leads to cancellation among logarithmic divergences of each Feynman diagram; the contribution of the KK graviton much heavier than the muon shows non-decoupling. The finiteness of the contributions of a graviton has been well known in supergravity models [13]. In the ADD model, the summation of all the KK graviton contributions with the cut-off M_S is compensated by the Planck scale suppression, which leaves finite contribution to the Δa_μ proportional to $(m_\mu/M_S)^2$.

In the RS model, there exist an infinitely large number of KK graviton states in the view point of our four-dimensional world, whereas the interaction is suppressed by only the electroweak scale. A naive summation of the finite contributions shall generate infinite contribution to the Δa_μ . A cut-off, corresponding to the M_S in the ADD case, is needed. We introduce n_c , the unitarity cut-off on the number of the KK graviton states. Then, we express the Δa_μ in terms of n_c and Λ_π . In fact, the necessity of introducing a cut-off in the RS model has been already known in its phenomenological study: Unitarity violation happens at high energies [14]. By examining the J -partial wave amplitudes of the elastic process $\gamma\gamma \rightarrow \gamma\gamma$, we shall derive the perturbative unitarity constraints on n_c and \sqrt{s}/Λ_π . It is to be shown that the recently measured Δa_μ can be accommodated in the RS model, with the natural values of n_c and Λ_π allowed by the unitarity constraint.

2. Randall-Sundrum Model and Δa_μ . For the hierarchy problem, Randall and Sundrum have proposed a five-dimensional non-factorizable geometry with the extra dimension compactified on a S_1/Z_2 orbifold of radius r_c [10]. Reconciled with four-dimensional Poincaré invariance, the RS configuration has the following solution to Einstein's equations:

$$ds^2 = e^{-2kr_c|\varphi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\varphi^2, \quad (2)$$

where $0 \leq |\varphi| \leq \pi$, and k is AdS_5 curvature. Two orbifold fixed points accommodate two three-branes, the hidden brane at $\varphi = 0$ and our visible brane at $|\varphi| = \pi$. The arrangement of our brane at $|\varphi| = \pi$ renders a fundamental scale m_0 to appear as the four-dimensional physical mass $m = e^{-kr_c\pi}m_0$. The hierarchy problem can be answered if $kr_c \approx 12$. From the four-dimensional effective action, the relation between the four-dimensional Planck scale M_{Pl} and the fundamental string scale M_5 is obtained by $M_{\text{Pl}}^2 = M_5^3(1 - e^{-2kr_c\pi})/k$.

The compactification of the fifth dimension leads to the following four-dimensional *effective* Lagrangian [14],

$$\mathcal{L} = -\frac{1}{M_{\text{Pl}}}T^{\mu\nu}h_{\mu\nu}^{(0)} - \frac{1}{\Lambda_\pi}T^{\mu\nu}\sum_{n=1}^{\infty}h_{\mu\nu}^{(n)}, \quad (3)$$

where $\Lambda_\pi \equiv e^{-kr_c\pi}M_{\text{Pl}}$. The coupling of the zero mode KK graviton is suppressed by usual Planck scale M_{Pl} , while those of the massive KK gravitons by the electroweak scale Λ_π . The masses of the KK gravitons are also at electroweak scale,

$$m_n = x_n(k/M_{\text{Pl}})\Lambda_\pi,$$

where x_n is the n -th root of the first order Bessel function. And the total decay width of the n -th KK graviton is $\Gamma_n = \rho m_n x_n^2(k/M_{\text{Pl}})^2$, where the ρ , fixed to be one, is a model-dependent parameter which is different according to the decay pattern of the KK graviton. The condition $k < M_{\text{Pl}}$ is to be imposed to maintain the reliability of the RS solution in Eq. (2) [15].

The Lagrangian in Eq. (3) then makes new contributions to the Δa_μ . The relevant Feynman diagrams mediated by the KK gravitons are presented in Fig. 1. We refer readers to Ref. [16] for the corresponding Feynman rules of the graviton, photon and fermion. Note that the gravitational Ward identity renders almost negligible, to leading order, the contributions of the terms containing two or more k_α 's in the massive graviton propagator. Here the k_α denotes the momentum of the graviton. A given n -th KK graviton state generates the Δa_μ , which is parameterized by [12]

$$\Delta a_\mu^{(n)} = \frac{1}{16\pi^2} \left(\frac{m_\mu}{\Lambda_\pi} \right)^2 \sum_f a_f^G = \frac{5}{16\pi^2} \left(\frac{m_\mu}{\Lambda_\pi} \right)^2, \quad (4)$$

where the f runs over five Feynman diagrams and the second equality holds for the case of $m_n \gg m_\mu$. As discussed in the previous section, naive summation over all the KK states would yield infinite contribution, i.e., $\Delta a_\mu \equiv \sum_n^\infty \Delta a_\mu^{(n)} \rightarrow \infty$. A cut-off is needed.

This requirement of a cut-off is expected since the RS model described by Eq. (3) is an effective theory. According to the analysis of the process $e^+e^- \rightarrow \mu^+\mu^-$ with the KK graviton effects, in the large k/M_{Pl} case the partial wave unitarity seems to be violated even at TeV scale as the resonant peaks of the KK gravitons become very wide and the cross section is greatly enhanced [14]. Since in the small $k/M_{\text{Pl}} \lesssim 0.3$ case the unitarity appears preserved at several TeV scales, possible unitarity violation of the RS model at high energy colliders has not been considered seriously yet. However, when we consider the loop effects by using an effective theory (the RS model) with an infinitely large number of states, we should determine the cut-off scale below which the perturbative calculations are reliable, and add only the contributions up to the cut-off scale. We introduce the cut-off on the effective number of KK graviton states, n_c . Then, the total RS contribution to the Δa_μ becomes

$$\Delta a_\mu^{RS} = \frac{5}{16\pi^2} \left(\frac{m_\mu}{\Lambda_\pi} \right)^2 n_c. \quad (5)$$

The scale of n_c will be estimated by examining the partial wave unitary bound in the process of $\gamma\gamma \rightarrow \gamma\gamma$. Note that the parameters $(\Lambda_\pi, k/M_{\text{Pl}})$ are constrained from the phenomenological studies of virtual exchange of the KK gravitons at LEP II and Tevatron Run I data; $\Lambda_\pi \gtrsim 1.1$ (0.65) TeV for the $k/M_{\text{Pl}} = 0.1$ (0.3).

In Fig. 2, we plot the Δa_μ^{RS} as a function of n_c for $\Lambda_\pi = 1, 2, 3$ TeV. It can be seen that the RS model can explain the recently reported Δa_μ from the SM prediction with $n_c \simeq 10, 50$, and 150, for $\Lambda_\pi = 1, 2$, and 3 TeV, respectively. As shall be shown in the next section, the scale of $n_c \simeq 10 - 100$ is natural in the sense that the partial wave unitarity is well preserved in this range. The scale of the heaviest KK graviton mass, m_{n_c} , then becomes of order 10 TeV, which can be regarded as a naive cut-off scale of the four-dimensional effective

Lagrangian in the RS scenario. In the next section, we will show that this is consistent with the cut-off scale for the perturbative unitarity.

Some discussions on the other RS effects rather than the KK gravitons are in order here. First in the RS scenario where the modulus field (called the radion) is inherent, its stabilization is needed for the consistency in a cosmological context [17]. According to the Goldberger and Wise stabilization mechanism, this radion can be an order of magnitude lighter than the Λ_π [17–19]. The radion contributions to the Δa_μ , however, have been too small to explain alone the Δa_μ of $\sim 4 \times 10^{-9}$ [20]. The effects of an extended RS model, where the SM gauge and fermion fields, are both in the bulk have been also examined [21]. The dominant contributions from bulk gauge bosons, bulk fermions, and Higgs bosons, however, generate *negative* contribution to the Δa_μ , which is difficult to be compatible with the recently reported positive deviation in a_μ . Moreover, the graviton loop contributions are not well-defined since the cancellation among logarithmic divergences does not occur due to non-universal couplings between the KK gravitons and the bulk SM fields.

3. Unitary Bound from $\gamma\gamma \rightarrow \gamma\gamma$ Scattering. In order to see whether the $n_c \simeq 10-100$ can naturally explain the Δa_μ in the effective theory interpretation, we consider another process to estimate the scale of n_c . The elastic process $\gamma\gamma \rightarrow \gamma\gamma$ is to be examined, focused on the unitarity bounds of the RS model: It has some merits such that the RS effects mediated by KK gravitons are dominant due to the absence of the SM contributions at tree level and thus the unitarity bounds of the RS model can be more sensitively probed compared to other processes. The requirement of partial wave unitarity shall constrain \sqrt{s}/Λ_π and the number of the KK graviton states, n_c . The J -partial wave amplitude is defined [22] by

$$a_{\mu\mu'}^J = \frac{1}{64\pi} \int_{-1}^1 d\cos\theta \, d_{\mu\mu'}^J(\cos\theta) \, [-i\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4}] \, , \quad (6)$$

where the $\mathcal{M}_{\lambda_1\lambda_2\lambda_3\lambda_4}$ is the helicity amplitudes, $\mu = \lambda_1 - \lambda_2$, $\mu' = \lambda_3 - \lambda_4$, and the $d_{\mu\mu'}^J$ is the Wigner functions [23]. Unitarity implies that the largest eigenvalue (χ) of $a_{\mu\mu'}^J$ is

to be $|\chi| \leq 1$. The reliability of perturbative calculations is approximately guaranteed by the conditions $|\chi| = 1$ and $|\text{Re}(\chi)| = 1/2$. The helicity amplitudes, of which the dominant contribution at high energies comes from the KK gravitons, are

$$\begin{aligned}\mathcal{M}_{++++} &= \mathcal{M}_{----} = -i \frac{s^2}{\Lambda_\pi^2} \sum_{n=1}^{n_c} [D_n(t) + D_n(u)] , \\ \mathcal{M}_{+--+} &= \mathcal{M}_{-++-} = -i \frac{u^2}{\Lambda_\pi^2} \sum_{n=1}^{n_c} [D_n(s) + D_n(t)] , \\ \mathcal{M}_{+---} &= \mathcal{M}_{-+++} = -i \frac{t^2}{\Lambda_\pi^2} \sum_{n=1}^{n_c} [D_n(s) + D_n(u)] ,\end{aligned}\tag{7}$$

where $D_n(s) = 1/(s - m_n^2 + im_n\Gamma_n)$ with m_n being the mass of the n -th KK graviton state. Note that two parameters $(\sqrt{s}/\Lambda_\pi, n_c)$ with a given k/M_{Pl} determine the helicity amplitudes, and thus χ . The odd J -partial wave amplitudes vanish due to Bose-Einstein statistics in the elastic $\gamma\gamma$ scattering. And we have $a_{22}^2 = a_{-2-2}^2$ and $a_{-22}^2 = a_{2-2}^2$ from the parity arguments. The non-vanishing eigenvalues χ_i are a_{00}^2 and $2a_{22}^2$.

In two limiting cases where $\sqrt{s}/\Lambda_\pi \ll (k/M_{\text{Pl}})x_n$ and $\sqrt{s}/\Lambda_\pi \gg (k/M_{\text{Pl}})x_n$, the two non-vanishing eigenvalues show converging behaviors. When $a_{\mu\mu'}^{J(n)}$ denotes the contribution of the n -th KK state to $a_{\mu\mu'}^J$, the $a_{00}^{2(n)}$ is approximated as

$$\begin{aligned}a_{00}^{2(n)} &\longrightarrow \frac{1}{384\pi} \frac{s^4}{\Lambda_\pi^8} \left(\frac{k}{M_{\text{Pl}}}\right)^{-6} \frac{1}{x_n^6}, & \text{for } \sqrt{s}/\Lambda_\pi \ll (k/M_{\text{Pl}})x_n, \\ a_{00}^{2(n)} &\longrightarrow \frac{1}{16\pi} \frac{s}{\Lambda_\pi^2} \left[\log \left\{ 2 \frac{k^2}{M_{\text{Pl}}^2} \frac{\Lambda_\pi^2}{s} x_n^2 \right\} + 3 \right], & \text{for } \sqrt{s}/\Lambda_\pi \gg (k/M_{\text{Pl}})x_n.\end{aligned}\tag{8}$$

There exist finite unitarity bounds $n_c \lesssim 1000$ at small \sqrt{s}/Λ_π , depending on the value of the parameter k/M_{Pl} . Similarly, we calculate the approximate formula for $a_{22}^{2(n)}$ in two limiting cases:

$$\begin{aligned}a_{22}^{2(n)} &\longrightarrow -\frac{1}{160\pi} \frac{s^2}{\Lambda_\pi^4} \frac{M_{\text{Pl}}^2}{k^2} \frac{1}{x_n^2}, & \text{for } \sqrt{s}/\Lambda_\pi \ll (k/M_{\text{Pl}})x_n, \\ a_{22}^{2(n)} &\longrightarrow -\frac{1}{64\pi} \frac{s}{\Lambda_\pi^2} \left[\frac{1}{16} \log \left\{ 2 \frac{k^2}{M_{\text{Pl}}^2} \frac{\Lambda_\pi^2}{s} x_n^2 \right\} + \frac{2}{5} \right], & \text{for } \sqrt{s}/\Lambda_\pi \gg (k/M_{\text{Pl}})x_n.\end{aligned}\tag{9}$$

The unitary bounds n_c are around $n_c \simeq 10 \sim 100$. The eigenvalue $2a_{22}^2$ generates stronger constraints compared to that of a_{00}^2 .

Figures 3 and 4 exhibit the exact numerical calculations of the unitarity bounds on $(\sqrt{s}/\Lambda_\pi, n_c)$ plane from the $\chi = a_{00}^2$ and $\chi = 2a_{22}^2$ constraints, respectively. We consider three values for $k/M_{\text{Pl}} (= 0.1, 0.3, 0.7)$. Note that the upper bounds on \sqrt{s}/Λ_π constrained from the perturbative unitarity are almost the same in the range of $n_c \simeq 10 - 100$ (such that $\sqrt{s} \lesssim 4\Lambda_\pi, 6.5\Lambda_\pi$, and $11\Lambda_\pi$ for $k/M_{\text{Pl}} = 0.1, 0.3$, and 0.7 cases, respectively). When we regard this upper bounds on \sqrt{s} as the cut-off scale of the effective RS model, we can see that this cut-off scale is compatible with the scale of m_{n_c} . Thus, the cut-off on the number of KK graviton states (n_c) which explains the reported Δa_μ is within the allowed region by the perturbative unitarity bounds.

4. Summary. To summarize, we have studied the effects of the Kaluza-Klein gravitons in the Randall-Sundrum model on the recent BNL measurements of the muon $(g-2)$ deviation from the SM prediction. It is known that the individual contribution of a heavy KK graviton to Δa_μ is finite. Since the four-dimensional effective theory in the RS model contains an infinitely large number of massive KK gravitons with the TeV suppressed couplings, a naive summation would yield infinite Δa_μ . A cut-off on the number of the KK gravitons has been introduced. Then the reported Δa_μ can be attributed to the RS effects with dozens (hundreds) of the n_c for $\Lambda_\pi = 1 \sim 2$ TeV (3 TeV). By examining the J -partial wave unitarity bounds in the elastic process $\gamma\gamma \rightarrow \gamma\gamma$, we have shown that this range of n_c is natural in the effective theory interpretation and the scale of the heaviest graviton mass (m_{n_c}) is compatible with the cut-off scale for the perturbative unitarity. Therefore, we conclude that the recently measured Δa_μ can be accommodated in the RS model.

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FIGURES

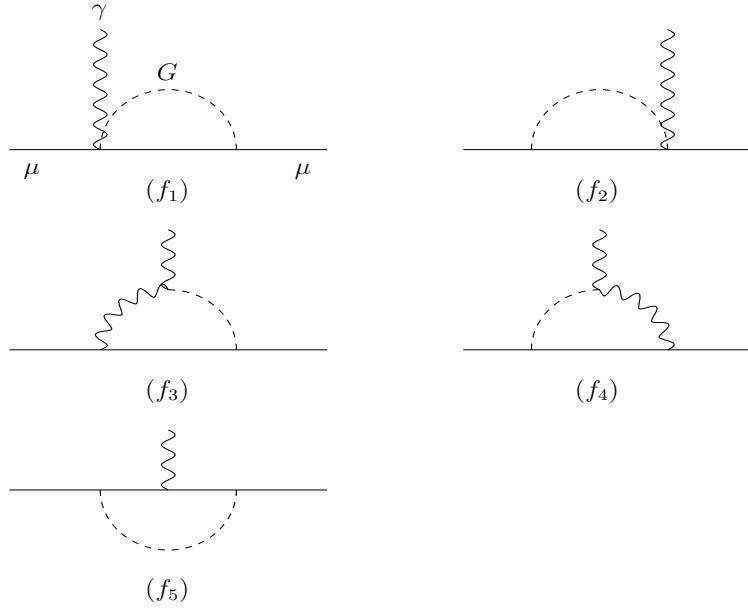


FIG. 1. The Feynman diagrams for the KK graviton contributions to Δa_μ in the RS model.

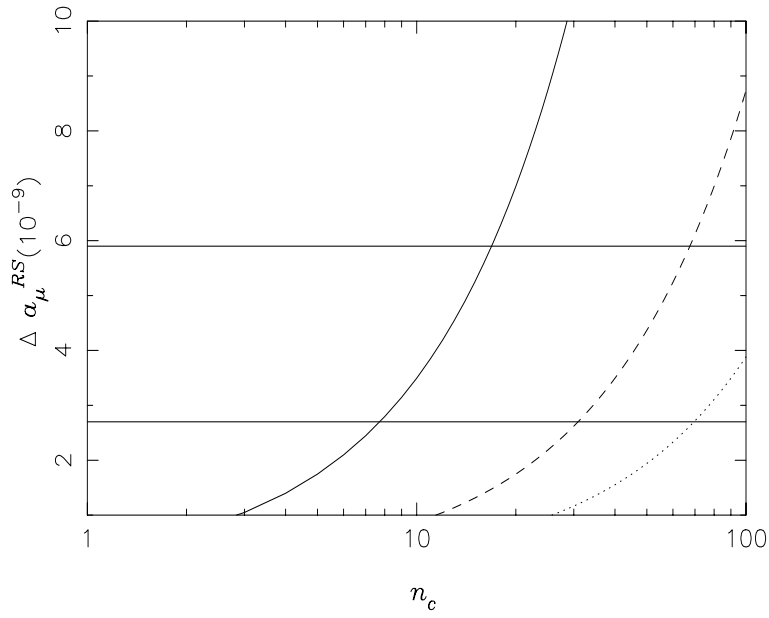


FIG. 2. The Δa_μ as a function of n_c for $\Lambda_\pi = 1$ (solid curve), 2 (dashed), and 3 (dotted) TeV. The horizontal lines denote the recent E821 data of Δa_μ within 1σ level.

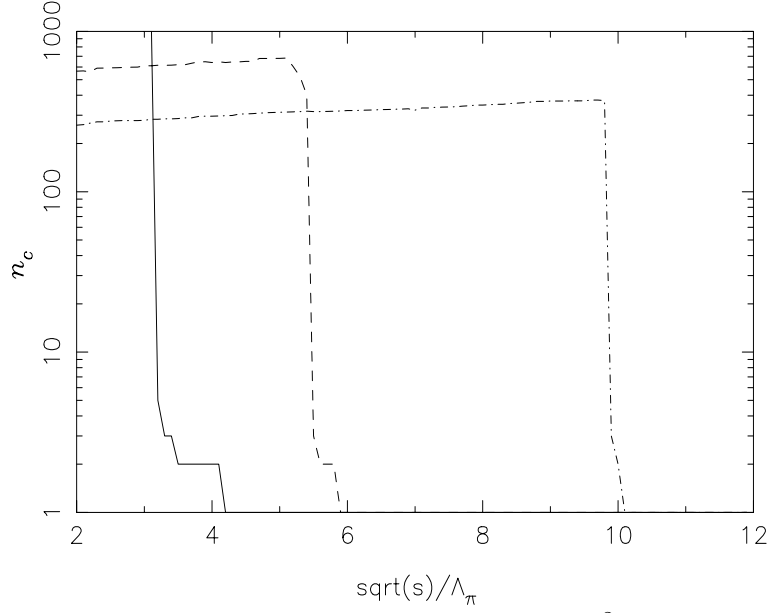


FIG. 3. The unitary bounds on $(\sqrt{s}/\Lambda_\pi, n_c)$ plane from the a_{00}^2 of the $\gamma\gamma \rightarrow \gamma\gamma$ process. The $k/M_{\text{Pl}} = 0.1$ (solid curve), 0.3 (dashed) and 0.7 (dot-dashed) cases are considered.

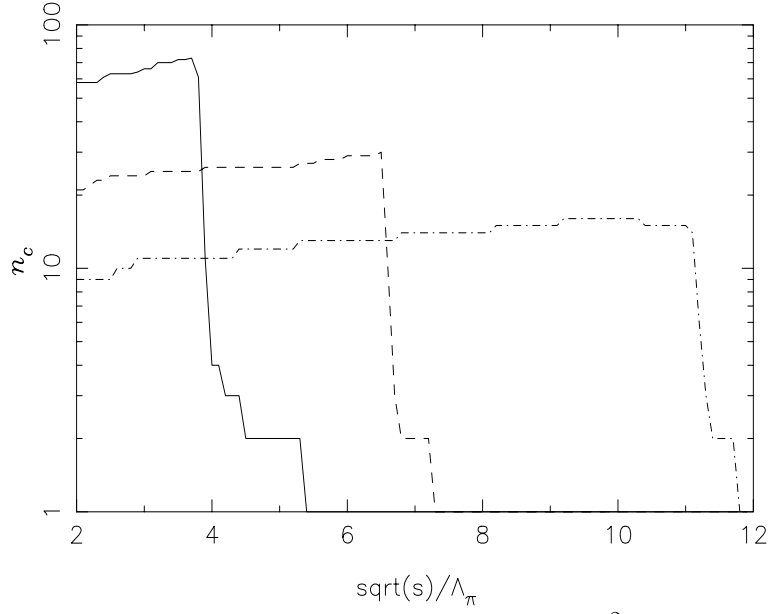


FIG. 4. The unitary bounds on $(\sqrt{s}/\Lambda_\pi, n_c)$ plane from the $2a_{22}^2$ of the $\gamma\gamma \rightarrow \gamma\gamma$ process. The $k/M_{\text{Pl}} = 0.1$ (solid curve), 0.3 (dashed) and 0.7 (dot-dashed) cases are considered.